A review of lenalidomide in combination with dexamethasone for the treatment of multiple myeloma

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Abstract: Lenalidomide (also known as Revlimid®, CC-5013) is an immunomodulatory derivative of thalidomide and has more potent anti-tumor and anti-inflammatory effects than thalidomide. The molecular mechanisms of anti-tumor activity of lenalidomide have been extensively studied in multiple myeloma (MM) both preclinical models and in clinical trials. Lenalidomide: directly triggers growth arrest and/or apoptosis of drug resistant MM cells; inhibits binding of MM cells to bone marrow (BM) extracellular matrix proteins and stromal cells; modulates cytokine secretion and inhibits angiogenesis in the BM milieu; and augments host anti-tumor immunity. Lenalidomide achieved responses in patients with relapsed refractory MM. Moreover, lenalidomide with dexamethasone (Dex) demonstrates more potent anti-MM activities than Dex both in vitro and in randomized phase III clinical trials. Specifically, the combination improved overall and extent of response, as well as prolonged time to progression and overall survival, resulting in FDA approval of lenalidomide with Dex for therapy MM relapsing after prior therapy.

Keywords: lenalidomide, dexamethasone, multiple myeloma

Introduction

Multiple myeloma (MM) is a B cell malignancy characterized by excess monotypic plasma cells in the BM in association with monoclonal protein in serum and/or urine, decreased normal immunoglobulin (Ig) levels, and lytic bone disease. The 2006 estimate of multiple myeloma incidence in the United States is 16,570 cases, with an estimated number of 11,300 deaths. Conventional therapies with alkylating agents, anthracyclines, and corticosteroids can extend patient survival to a median of 3–4 years (Gregory et al 1992; Group 1998), and high dose therapy followed by autologous transplantation can modestly prolong median survival to 4–5 years (Fermand et al 1998; Lenhoff et al 2000). Attempts to improve autografting include repeated use of high dose therapies (Desikan et al 2000; Attal et al 2003), as well as immune strategies to treat minimal residual disease post-transplant (Massaia et al 1999) can improve outcome in some studies, few, if any, patients are cured. MM remains incurable due to the development of tumor cell resistance to all therapies, highlighting the urgent need for novel treatment strategies.

Thalidomide (Thal) has shown to be useful in various diseases including MM; however, it is a potent teratogen and causes side effects including peripheral neuropathy (Tseng et al 1996). Attempts were therefore made to develop Thal analogs which are more potent and have less adverse effects: lenalidomide ($C_{13}H_{13}N_3O_3$, MW = 259.26) is one such analog belonging to the class ofimmunomodulatory drugs (IMiDs) developed by the drug discovery program.

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Preclinical studies of lenalidomide

Overview (Figure 1)

The interaction of multiple myeloma (MM) cells with bone marrow (BM) extracellular matrix (ECM) proteins and BM accessory cells, BM stromal cells (BMSCs), osteoblasts, osteoclasts, endothelial cells, as well as other factors in the BM milieu (ie, cytokines, angiogenesis) plays a crucial role in MM pathogenesis and drug resistance (Damiano et al 1999; Akiyama et al 2002; Hideshima and Anderson 2002; Hideshima et al 2003, 2004, 2006; Chauhan et al 2004). These accessory cells not only physically interact with MM cells, but also secrete growth and/or anti-apoptotic factors such as interleukin (IL)-6, insulin-like growth factor (IGF)-1, vascular endothelial growth factor (VEGF), and tumor necrosis factor (TNF)-α (Akiyama et al 2002; Chauhan et al 1996, 2004, 2005; Catley et al 2004; Hideshima et al 2006). Delineation of the mechanisms of BM stromal cell (SC)-mediated MM cell proliferation, survival, drug resistance, and migration therefore provides the framework for identification and validation of novel therapeutic targets.

Within the BM microenvironment, several proliferative/antiapoptotic signaling cascades are activated in MM cells: phosphatidylinositol-3 kinase (PI3K)/Akt (also known as protein kinase B); I κ B kinase (IKK)/nuclear factor κ-B (NFκB); Ras/Raf/mitogen-activated protein kinase (MAPK) kinase (MEK)/extracellular signal-related kinase (ERK); and Janus kinase (JAK) 2/signal transducers and activators of transcription (STAT)-3 (Figure 1, Table 1). These signaling cascades mediate: cytoplasmic sequestration of many transcription factors; upregulation of cyclin D and anti-apoptotic Bcl-2 family members; as well as augmentation of telomerase activity (Hideshima et al 2001a; Akiyama et al 2002). Importantly, these molecular events are triggered by both MM cell adherence to BMSCs and by cytokines secreted from BMSCs (Dankbar et al 2000; Hideshima et al 2004; Mitsiades et al 2004). Cytokines secreted from MM cells and BMSCs and other cells may in turn further augment cytokine secretion.

Novel biologically based agents target not only the MM cell, but also MM cell–host interactions, cytokines, and their sequelae in the BM milieu. Thalidomide and

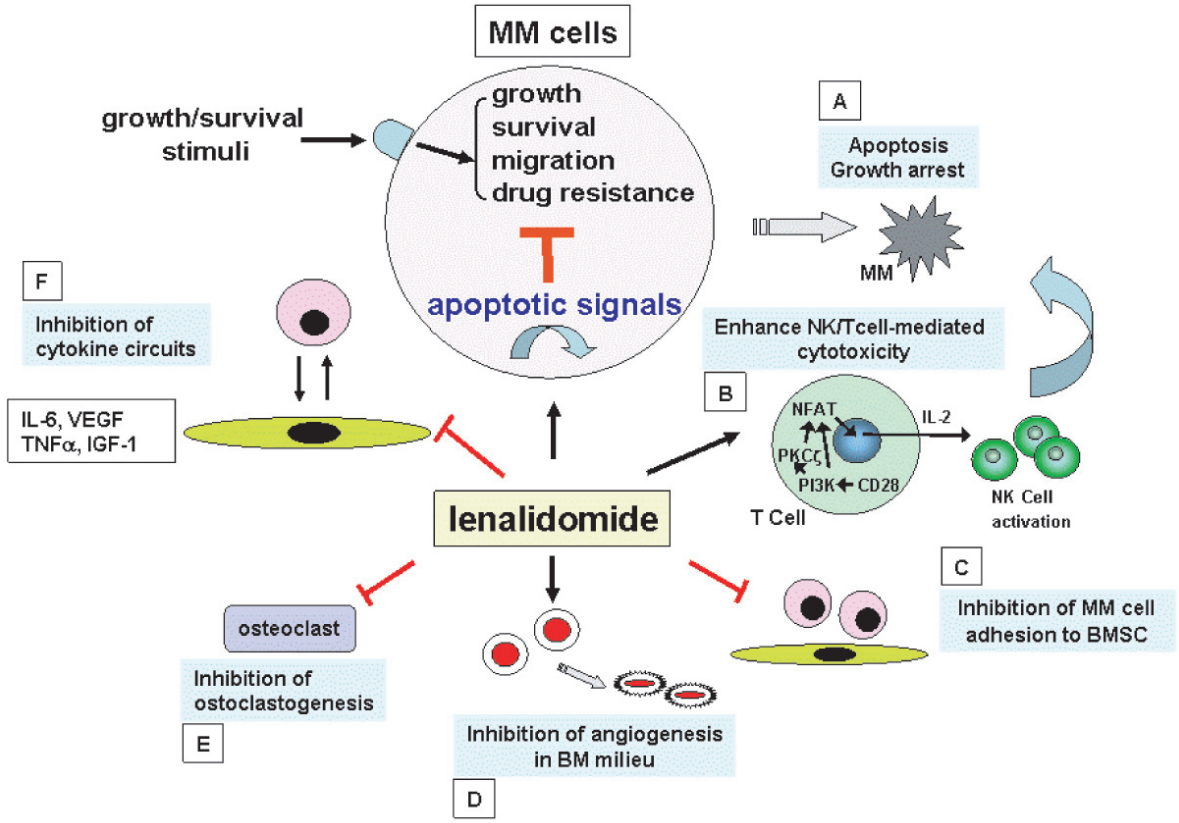

Figure 1 Potential mechanisms of action of anti-MM activity of lenalidomide. Lenalidomide: directly induces tumor cell apoptosis and/or growth arrest (**A**); enhances NK and/or NK cell activity via activation of CD28/NF-AT2 pathway (**B**); inhibits MM cell adhesion to host microenvironment (**C**); inhibits angiogenesis (**D**); inhibits osteoclastogenesis (**E**); as well as inhibits cytokine secretion (**F**).

its immunomodulatory derivative (IMiD) lenalidomide (Revlimid®; Celgene Corp., Summit, NJ, USA) are examples of such agents targeting the tumor cell in its BM milieu which can achieve responses even in refractory relapsed MM. Lenalidomide may inhibit MM cell growth by several different mechanisms (Figure 1). First, lenalidomide has a direct effect on MM cells to induce G1 growth arrest or apoptosis even of drug resistant cells (Hideshima et al 2000; Mitsiades et al 2002). Second, lenalidomide inhibits adhesion of MM cells to BMSCs, and thereby can overcome cell adhesion mediated drug resistance (CAM-DR); third, lenalidomide inhibits bioactivity and/or secretion in MM cells and/or BM stromal cells of cytokines [eg, interleukin (IL)-6, IL-1β, IL-10, and tumor necrosis factor (TNF)α] which augment MM cell growth, survival, drug resistance, migration, and expression of adhesion molecules. Importantly, lenalidomide is several thousand fold more potent than Thal at inhibiting TNFα/IL-1β secretion from mononuclear cells stimulated with lipopolysaccharide (LPS) in vitro (Corral et al 1999; Muller et al 1999). Fourth, vascular endothelial growth factor (VEGF) and basic fibroblast growth factor (bFGF) are secreted by MM cells and/or BMSCs, and lenalidomide may inhibit activity of VEGF, bFGF, and angiogenesis in MM. Lenalidomide also acts against MM through immunomodulatory effects such as augmentation of activity of cytotoxic T-cells and natural killer (NK) cells, associated with secretion of IL-2 and interferon-γ (Davies et al 2001; LeBlanc et al 2004; Hayashi et al 2005).

Bone destruction is a hallmark of MM, with 70%–80% of patients manifesting bone involvement. Recently, Anderson et al demonstrated that an IMiD CC-4047 (Actimid®; Celgene Corp., Summit, NJ, USA) inhibits osteoclastgenesis via downregulation of transcription factor PU.1 (Anderson et al 2006). Lenalidomide also has inhibitory effect on osteoclastogenesis (Terpos et al 2007).

Table 1 Selected ongoing clinical trials of lenalidomide based combination treatment in multiple myeloma

Agent	Phase	Patient
Perifoine + Dex	I	Rel/ref
Hepatitis B vaccine	I	Rel/ref
Doxorubicin + Dex	I/II	Rel/ref
Bortezomib + Dex	I/II	Newly diagnosed
Bortezomib + Dex	II	Rel/ref
Bevacizumab + Dex	II	Rel/ref
Clarithromycin + Dex	II	Newly diagnosed
Dex	III	Newly diagnosed
Dex	III	Previously treated
Dex	IV	Previously treated

Direct anti-tumor activities of lenalidomide

Although the targets of whereby lelalidomide mediates anti-tumor activity of lenalidomide have not been fully delineated, several studies have examined the molecular mechanisms mediating sequelae of lenalidomide. Our previous studies demonstrated that lenalidomide induces G0/G1 growth arrest associated with $p21^{Cip1}$ upregulation and/or apoptosis which is mediated via caspase-8 activation (Hideshima et al 2000; Mitsiades et al 2002). Lenalidomide inhibits LPS-mediated induction of Cox-2 and prostaglandin E2 (PGE2) production by a post-transcriptional mechanism in RAW 364.7 cells (Fujita et al 2001), suggesting that the anti-tumor activity induced by lenalidomide may also be due to inhibition of Cox-2 and PGE2. Lenalidomide inhibits nuclear factor (NF)-κB subunit activity in MM cell lines (Mitsiades et al 2002), which is consistent with reports that Thal inhibits DNA binding activity of the p50/p65 NF-κB triggered by TNFα and IL-1β in Jurkat cell line (Keifer et al 2001) and in PBMCs (Rowland et al 2001). Since NF-κB plays an essential role in cell cycle regulation, cell survival, anti-apoptosis, and cytokine production in MM cells (Hideshima et al 2001b, 2002), inhibition of NF-κB activity by lenalidomide may also enhance or restore sensitivity to other chemotherapeutic agents. Specifically, we have demonstrated that MM cell adhesion-mediated upregulation of IL-6 is mediated via NF-κB activation (Chauhan et al 1996; Hideshima et al 2002). Recently, Stewart et al (2004) reported pharmacogenomic studies suggesting that hyperactivation of the Wnt signaling antagonist DKK-1 is associated with response to the immunomodulators Thal and lenalidomide. Furthermore, β-catenin expression is downregulated by lenalidomide in MM cell lines.

Lenalidomide in combination with Dex is one of the most promissing MM novel treatment options. It induces at least additive direct cytotoxicity in MM cells (Hideshima et al 2000), associated with activation of dual apoptotic signaling cascades: Dex induces caspase-9 (Chauhan et al 2001; Hideshima et al 2001a) and lenalidomide triggers caspase-8 activation (Mitsiades et al 2002) (Figure 2). Most recently, enhanced anti-MM activity of rapamycin, a specific mTOR inhibitor, in combination with lenalidomide has been reported (Raje et al 2004). In this study, the combination of rapamycin plus lenalidomide overcomes drug resistance in MM cell lines resistant to conventional chemotherapy. Interestingly, differential signaling cascades, including the ERK and PI3-K/Akt pathways, are targeted by these drugs individually and in combination, suggesting the molecular mechanism by which they inhibits MM growth and survival.

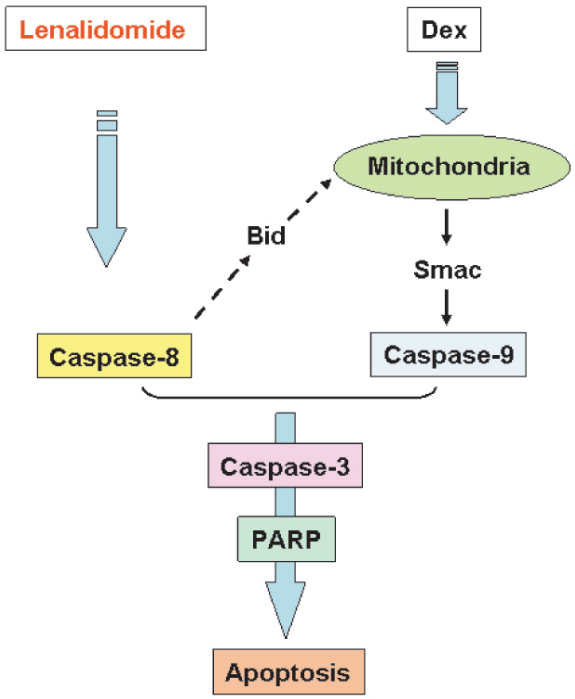

Figure 2 Potential mechanisms of synergistic cytotoxicity by lenalidomide plus Dex treatment in MM cells. Lenalidomide triggers caspase-8 dependent apoptosis, whereas Dex induces caspase-9 dependent apoptosis. The combination therefore triggers dual apoptotic signaling cascades.

Anti-angiogenic activity

Previous studies have shown that oral administration of lenalidomide attenuates growth factor-induced angiogenesis in vivo. This effect is correlated with the inhibitory effect of lenalidomide on growth factor-induced Akt phosphorylation, thereby providing a potential mechanism for its anti-migratory and subsequent anti-angiogenic effects (Dredge et al 2005). In MM, an anti-angiogenic effect of Thal in vitro has been demonstrated (D'Amato et al 1004; Singhal et al 1999; Lentzsch et al 2002; Fujita et al 2004); however, to date no strong evidence of an anti-angiogenic effect of lenalidomide in vivo has been demonstrated. Moreover, Singhal et al (1999) reported no correlation of BM angiogenesis with response to Thal in patients with relapsed refractory MM, suggesting that lenalidomide may mediate its anti-MM activity via mechanisms other than anti-angiogenesis.

Immunomodulatory activities

A unique feature of the anti-tumor effect of Thal and lenalidomide is their ability to modulate and potentiate host immune responses against MM. Several studies have demonstrated the effects of lenalidomide on peripheral blood lymphocytes (Davies et al 2001; Haslett et al 2003; LeBlanc et al 2004; Hayashi et al 2005). Co-culture of naive splenocytes with anti-CD3 monoclonal antibody and IMiD1 (Actimid®) directly costimulates T cells and increases Th-1-type cytokines. Most excitingly, IMiDs augment CTL and NK cell activity against MM cell lines and autologous MM cells, associated with increased IL-2 levels in serum (Davies et al 2001). Although Thal/IMiDs induce IL-2 secretion from T cells (Corral et al 1999; Shannon et al 2000), the mechanisms whereby these compounds induce IL-2 production from T cells has not totally been defined. Importantly, our recent studies demonstrated that lenalidomide significantly costimulates proliferation of CD3+ T cells induced by CD3 ligation, immature dendritic cells (DCs; SI, 2.1), or mature DCs (SI, 2.6). T-cell proliferation triggered by DCs is abrogated by cytotoxic T lymphocyte antigen 4-immunoglobulin (CTLA-4-Ig). Lenalidomide also overcomes the inhibitory effects of CTLA-4-Ig on Epstein-Barr virus and influenza-specific CD4 and CD8 T-cell responses, as measured by cytokine capture and enzyme-linked immunosorbent spot (ELISPOT) assays. Importantly, lenalidomide triggers tyrosine phosphorylation of CD28 on T cells, followed by activation of NF-κB (LeBlanc et al 2004). Furthermore, we have demonstrated that IMiDs facilitate the nuclear translocation of nuclear factor of activated T cells (NF-AT)-2 and activator protein-1 via activation of PI3-K/Akt signaling, with resultant IL-2 secretion. IMiDs enhance both NK cell cytotoxicity and ADCC induced by triggering IL-2 production from T cells (Hayashi et al 2005). These studies therefore define the molecular mechanisms whereby lenalidomide triggers NK cell-mediated cytotoxicity against MM cells, further supporting their therapeutic use in MM. More recently, we have shown that lenalidomide enhances ADCC induced by SGN-40, a humanized IgG1 anti-CD40 monoclonal antibody (Tai et al 2005).

Clinical studies of lenalidomide

Pharmacokinetics

Pharmacokinetics (PK) of lenalidomide in MM patients has been reported by Wu and Scheffler (2004) at American Society of Clinical Oncology in 2004. In this single-center, open-label, non-randomized, phase I dose escalation study in relapsed and refractory MM, the doses of lenalidomide used were 5, 10, 25 or 50 mg/day orally for 28 days. Blood samples were collected before and at 15 min, 30 min, 45 min, 1 h, 1.5 h, 2 h, 2.5 h, 3 h, 4 h, 6 h, 8 h, 10 h, 12 h, 18 h, 24 h, 48 h, and 72 h after administration on both days 1 and 28. No lenalidomide dose-limiting toxicity was observed at any dose level within the first 28 days. Absorption of lenalidomide was rapid on both day 1 and 28, with t_{max} ranging from 0.7 to 2.0 h

at all dose levels. Plasma levels of lenalidomide declined in a monophasic manner, with elimination half-life ranging from 2.8 to 6.1 h on both days 1 and 28 at all four doses. No plasma accumulation was observed upon multiple dosing. Importantly, daily oral doses of lenalidomide up to 50 mg produced no dose-limiting toxicity within the first 28 days.

The other PK study has been reported by Richardson et al (2006). In this study, plasma concentration of lenalidomide was determined in 39 patients during the first and second cycles in both 15 mg and 30 mg dose groups, and when Dex was added due to progressive disease (PD) or stable disease (SD) on lenalidomide alone. The mean minimum (C_{min}) plasma lenalidomide concentrations on days 1, 2, 3, 4, and 21 during the first and second 21-day cycles of lenalidomide alone and with the addition of Dex are shown for the 30 mg once-daily and 15 mg twice-daily cohorts. The average C_{min} plasma levels were less in the twice-daily compared with daily dosing regimens. No obvious effect on lenalidomide plasma concentrations was seen with addition of Dex in either once- or twice-daily treatment.

Clinical trials of lenalidomide

Only a limited number of reports are available for clinical studies of lenalidomide (Bartlett et al 2004). A phase I clinical study of lenalidomide was completed at Dana-Farber Cancer Institute (Richardson et al 2002a). In this study, dose-escalation (5 mg/day, 10 mg/day, 25 mg/day, and 50 mg/day) of lenalidomide was evaluated in 27 patients (median age 57 years; range, 40–71 years) with relapsed and refractory relapsed MM (Richardson et al 2002b). These patients received a median of 3 (range, 2–6) prior regimens, including autologous stem cell transplantation and Thal in 15 and 16 patients, respectively. In 24 evaluable patients, no dose-limiting toxicity (DLT) was observed in patients treated at any dose level within the first 28 days; however, grade 3 myelosuppression developed after day 28 in all 13 patients treated with 50 mg/day lenalidomide. Dose reduction to 25 mg/day was well tolerated in 12 patients and therefore considered to be the maximal tolerated dose (MTD). Most importantly, no significant somnolence, constipation, or neuropathy, the most common toxicities of Thal, have been seen in any cohort. Best responses of at least 25% reduction in paraprotein occurred in 17 of 24 (71%) patients (90% confidence interval [CI], 52%–85%), including 11 (46%) patients who had received prior Thal; stable disease (less than 25% reduction in paraprotein) was observed in an additional 2 (8%) patients. This study therefore demonstrates that lenalidomide can overcome conventional drug resistance, even resistance to Thal. Given that lenalidomide is an oral agent, it is currently being evaluated in a randomized trial post autografting in an attempt to prolong progression free and overall survival.

A multicenter, open-label, randomized phase II study to evaluate 2 dose regimens of lenalidomide for relapsed, refractory MM has been performed. In this study, 70 patients were randomized to receive either 30 mg once-daily or 15 mg twice-daily oral lenalidomide for 21 days of every 28-day cycle. An additional 32 patients received 30 mg once daily. Patients with progressive or stable disease after 2 cycles received additional Dex. Responses were evaluated according to European Group for Blood and Marrow Transplantation (EBMT) criteria. Overall response rate (CR+PR+MR) to lenalidomide alone was 25%; 24% for 30 mg once-daily and 29% for 15 mg twice-daily cohort. Median overall survival in 30-mg once-daily and 15 mg twice-daily groups was 28 and 27 months, respectively. However, median progression-free survival was 7.7 months on 30 mg once-daily versus 3.9 months on 15 mg twice-daily lenalidomide. Dex was added in 68 patients and 29% responded. Importantly, time to first occurrence of clinically significant grade 3/4 myelosuppression was shorter in the 15 mg twice-daily group (1.8 months) than 30 mg once-daily (5.5 months, $p = 0.05$) group. Moreover, analysis of the first 70 patients showed increased grade 3/4 myelosuppression in patients receiving 15 mg twice-daily (41% vs 13%, $p = 0.03$). This study indicate that lenalidomide is active and well tolerated in relapsed, refractory myeloma, with the 30-mg once-daily regimen providing the basis for future studies as monotherapy and with Dex (Richardson et al 2006).

Clinical studies of lenalidomide in combination with Dex

As described above, preclinical studies have demonstrated the efficacy of combination treatment of lenalidomide with Dex in MM and several clinical trials of this combination treatment have been completed.

In two double blind, multicenter, international phase III clinical trials (MM-009, North American, 353 patients; MM-010, Europe, Australia, and Israel, 351 patients), patients with relapsed or refractory MM not resistant to Dex were treated with Dex 40 mg daily on days 1–4, 9–12, and 17–20 every 28 days and were randomized to receive either lenalidomide 25 mg daily orally on days 1–21 every 28 days or placebo. At a median follow-up from randomization of 17.1 months (MM-009) and 16.5 months (MM-010), both studies show significant improvement with lenalidomide

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